Development and Assessment of Clinically-Oriented Tools to Identify Ankle Proprioception, Ankle Instability, and Postural Control Relationships

Undergraduate Honors Thesis

Presented in Partial Fulfillment of the Requirements for Graduation with Honors Research Distinction in the Department of Biomedical Engineering at The Ohio State University

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March 2018

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Abstract

Proprioception is an essential component to balance and postural control and is defined as the ability to sense the position and movements of limb segments relative to one another. Proprioception and postural control deficits are associated with many health conditions and evaluation of these measures is an essential first step in identifying at-risk patients and beginning therapeutic intervention. There is also a gap in knowledge in how ankle joint position sense (a component of proprioception) and postural control are related. This project had four objectives. The first was to adapt a Nintendo Wii Balance Board into a clinical tool to evaluate postural control. Second was to determine the reliability of using a free iOS application CoreX Therapy to assess ankle proprioception. The third objective was to evaluate the relationship between ankle instability and postural control and the fourth was to investigate how ankle instability and ankle proprioception are related. Data for this study were collected at the 2017 American Society of Biomechanics' Annual Conference. Participants self-reported their ankle instability through a questionnaire and their ankle joint position sense was assessed using the CoreX Therapy application. Participants also performed three trials of quiet standing on a Wii Balance Board and Bertec Force Plate for assessment of postural control. Data were collected from forty-five diverse participants. The CoreX Therapy application was determined to be a moderately reliable tool for assessing ankle proprioception with an ICC(1,k) of 0.741. The average absolute error from ten trials of active joint positioning excluding the most and least accurate trial was used as the measure of ankle proprioception. There was no significant difference ($p = 0.21$) in the average absolute error between the groups with and without ankle instability. Postural control parameters did not correlate with active ankle joint position sense with all Pearson correlation values less than 0.2. This study developed and used novel, clinically-oriented tools to assess

postural control, and ankle proprioception. It established that healthy populations do not have significant correlations in active ankle joint positioning with postural control and self-reported ankle instability.

Acknowledgements

I would like to thank Dr. Ajit Chaudhari for his invaluable mentorship over the past three years. It was a visit to his lab in 2012, during my sophomore year of high school, that inspired me to pursue biomedical engineering and eventually biomechanics research. From advice three years ago on choosing an engineering major to encouraging me to pursue an Undergraduate Honors Thesis, I would truly not be where I am today without the guidance and opportunities he provided. Thank you to Dr. Rob Siston for serving on my thesis committee and providing me support and guidance throughout my undergraduate years. I would also like to thank Dr. Scott Monfort for his mentorship and leadership on this project from conception through data collection, processing, and interpretation. Thank you to the rest of the members of the Sports Biomechanics Lab for their willingness to answer questions, assistance in data collection, and continuous valuable feedback. I would like to also thank Dr. Kim Bigelow and her students from the University of Dayton for their help collecting data this summer during the American Society of Biomechanics Annual Meeting. Lastly, I would thank the Ohio State College of Engineering for awarding me an Undergraduate Thesis Research Grant.

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Chapter 1: Introduction

1.1 Postural Control and its Assessment in the Clinic

Maintaining balance through postural control is a complex task that requires the integration of visual, vestibular, and proprioceptive sensory information together with reliance on the musculoskeletal system.[1] Dysfunctions in postural control and impaired standing balance have been associated with many health conditions[2] and identified as risk factors for falls in the elderly[3,4] and certain sports injuries.[5,6] A clinical assessment of balance is important because it can provide prediction and prevention of falls, rehabilitation of neurological or orthopedic patients, improvement of sports performance, and reduction of injury risk.[7–11]

Currently, parameters derived from center of pressure (CoP) trajectories measured by a laboratory grade force plate (FP) are the gold standard for quantifying postural control.[12] Using a FP to assess standing balance provides high quality data, but most FPs are expensive, difficult to set up, and hard to transport making assessment of balance limited to specialized labs.[13,14] These limitations have led to recent investigations of the Nintendo Wii Balance Board (WBB; Nintendo, Kyoto, Japan) as an alternative tool for assessing postural control.[14–16] The WBB is low cost (~$100 USD), highly portable, and reports CoP data using four force transducers (similar to a FP) making it attractive for use in clinical settings. Collecting data with a WBB does have limitations such as a lower sampling rate and a larger amount of noise,[17] but multiple studies have shown the WBB to still be a reliable tool for collecting balance data[12–14] and distinguishing between healthy subjects and populations known to have postural control impairments.[15,18,19] The first objective of this project was to create a program and data processing protocol that makes a Nintendo Wii Balance Board a viable tool for collecting accurate CoP data

in research and clinical settings. Accomplishing this objective will enable balance assessment in any setting where the use of a FP is financially prohibitive.

1.2 Ankle Proprioception and its Assessment in the Clinic

Proprioception is an essential component to balance and postural control and is defined as the ability to sense the position and movements of limb segments relative to one another.[20] It provides information relating to the sense of movement (kinesthesia), the position of joints (joint position sense), velocity of muscular contraction, and the force associated with muscular contractions.[21] Proprioception is at risk of deterioration with factors such as aging, peripheral neuropathy, osteoarthritis, and ligament injury.[22] Decreased proprioception has been specifically associated with a higher risk of falls in patients with peripheral neuropathy.[23,24] Being able to measure proprioception in the clinic is important as rehabilitation in patients with decreased proprioception may mitigate declines in their functional stability.[25,26]

Typically, proprioception is measured using a Biodex isokinetic dynamometer or custom-built devices that record joint position sense (JPS), a component of propioception.[25,28] These methods have cost, space, ease-of-use, and portability barriers that impede the ability of clinicians to measure proprioception in populations that are at risk of having deficits. Because of this, mobile device applications have increasingly been investigated as an alternative method of measuring human movement and proprioception, but the ability of these apps to quantify specifically ankle proprioception is unknown. CoreX Therapy (Perfect Practice, Inc.) is an iOS app that has previously demonstrated utility for quantifying core stability through the measurement of pelvic tilt.[27] Recent research has investigated using this application as a clinically-relevant tool for measuring ankle joint position sense, but the reliability of this novel tool has not been established. Therefore, the second objective of this study was to establish the

reliability of the CoreX Therapy application as a tool for assessing ankle proprioception in the clinic.

1.3 Ankle Proprioception and Postural Control Relationship

Falls in the elderly and sports injuries in young athletes are two major health risk factors that are associated with over $60 billion in medical costs annually.[29,30] While these events typically have multifactorial causes, instability during stance and ambulation have prospectively been identified as risk factors for falls in the elderly[3,4] and certain sports injuries[5,6]. Proprioception is acknowledged as an integral afferent signal involved in coordinated and safe movements. Impaired proprioception has been identified in fall prone populations and as a risk factor for sustaining musculoskeletal lower extremity injuries in sports. In addition to shortcomings in how postural control and proprioception can be quantified in the clinic, investigations into the relationship between proprioception and postural control have largely focused on nerve conduction, cutaneous sensation, and/or kinesthesia[31] with scarce information on the relationship between joint position sense and balance. The third objective of this research was to address existing gaps in knowledge by investigating the relationship between a quantitative measure of ankle joint position sense and postural control.

1.4 Ankle Proprioception and Ankle Instability Relationship

Lateral ankle sprain is a common injury that has high rates of recurrence for reasons that are not well understood. Researchers have hypothesized that underlying functional ankle instability (FAI) predisposes individuals to re-injury after lateral ankle sprains and loss of proprioceptive input causes position-sense deficits leading to improper positioning of the foot just before foot contact.[32]

Previous studies have investigated the connection between ankle joint position sense and ankle instability, but have reported varying results.[32] A targeted, quantifiable approach to establish the relationship between ankle proprioception and ankle instability is needed to provide further insight. Therefore, the fourth objective of this research was to investigate the relationship between self-reported ankle instability and a quantitative measure of ankle proprioception using the CoreX Therapy application as a novel, clinically-oriented proprioception test.

1.5 Overview of Thesis

This thesis consists of five chapters. The second chapter describes the methodology of this research, including developing the clinical tools, data collection, and statistical analysis. Chapter 3 provides the results from this research study. The fourth chapter discusses the implications of these results and the fifth chapter details conclusions drawn from the is research and potential future work.

Chapter 2: Methodology

2.1 Development of Postural Control Clinical Tool

The first objective of this research was to develop a custom program that allowed the WBB to collect research-quality CoP data therefore enabling it to be a clinical tool for assessing postural control. A custom program was developed in LabVIEW by adapting an existing program that collected CoP data from a Bertec FP hardwired to a laptop.[33] The program was adapted to record and save all data for standard postural control testing using a Bluetooth connection to the WBB. After the program was adapted and consistently collected data, the WBB and program were calibrated. The WBB has four force transducers on the bottom of the board (Figure 1), one in each corner, that measure force. The first step in calibration was

applying a load to each corner individually (while the balance board was upside down) with five different known weights. The weight measured by the WBB was recorded. The known true weight was plotted versus the measured weight and a linear fit was applied to the data to get slope and intercept calibration values for each of the four force transducers (Figure 2).

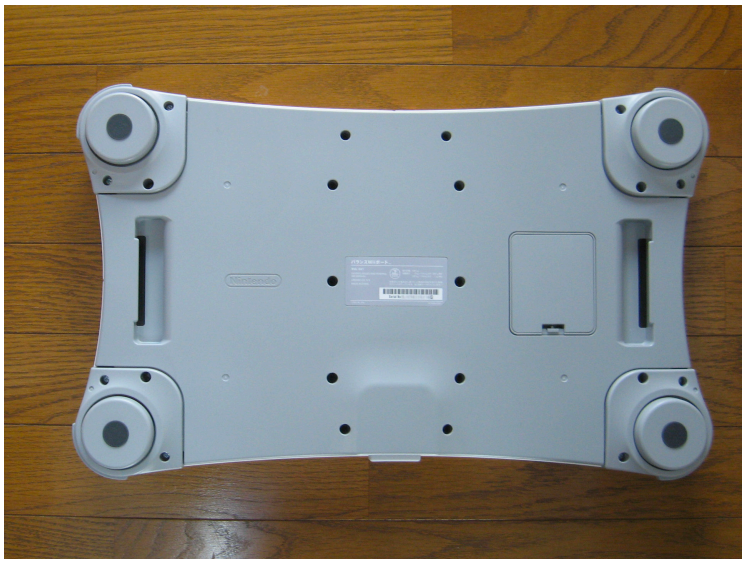

Figure 1: Bottom of Nintendo Wii Balance Board.

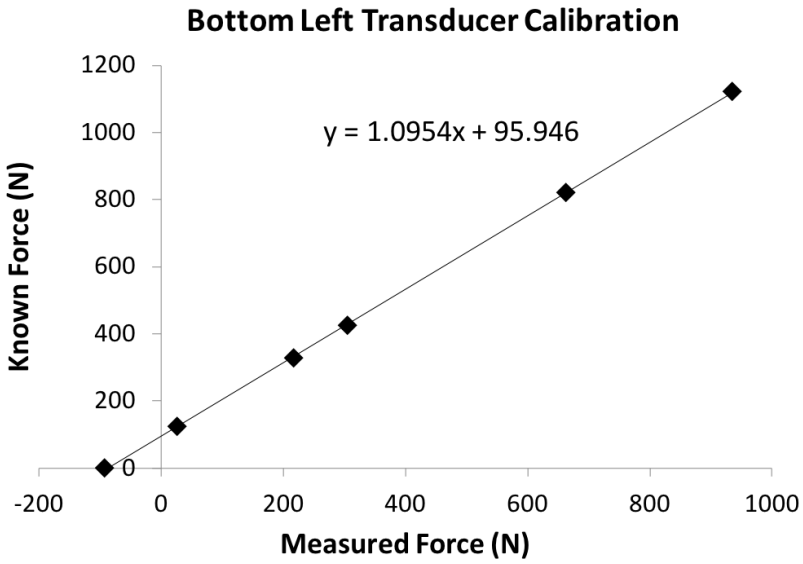

Figure 2: Sample calibration plot for bottom left WBB transducer.

Next, single point loads were added to the WBB right side up (Figure 3) at a number of known x and y positions from the center of the board. The force values registered by the WBB at each corner were recorded. Then, the calibration equations determined previously for each transducer were used with the recorded force values to get calibrated force readouts for each of the four transducers. These calibrated values were then used in the equations below. Equation 1 was used to determine the calculated CoP in the x direction and equation 2 was used to determine the CoP in the y plane. *X* and *Y* are the length of the WBB in the two planes and are 433mm and 238mm respectively. *F* is force measured, *TR* is top right sensor, *TL* is top left sensor, *BR* is bottom right sensor, and *BL* is bottom left sensor.

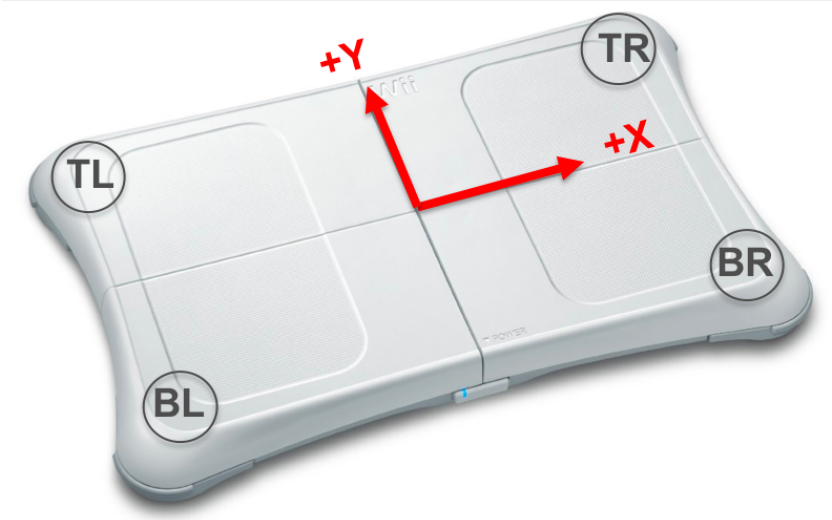

Figure 3: Nintendo Wii Balance Board (image adapted from: https://www.absolutegadget.com).

$$CoP_{WBB_x} = \frac{X}{2}\frac{(F_{TR} + F_{BR}) - (F_{TL} + F_{BL})}{F_{TR} + F_{BR} + F_{TL} + F_{BL}} \quad (1)$$

$$CoP_{WBB_y} = \frac{Y}{2}\frac{(F_{TR} + F_{TL}) - (F_{BR} + F_{BL})}{F_{TR} + F_{BR} + F_{TL} + F_{BL}} \quad (2)$$

Next the known CoP values in the x direction (CoP_x) were plotted against the calculated CoP_x values. A linear fit was applied to the data and the slope and intercept values were recorded. The same was done for the known and calculated CoP values in the y direction (Figure 4). These slope and intercept values were then implemented into the LabVIEW program to finish the calibration procedure. This program was later further adapted to simultaneously collect data from the WBB and Bertec FP for use in data collection.

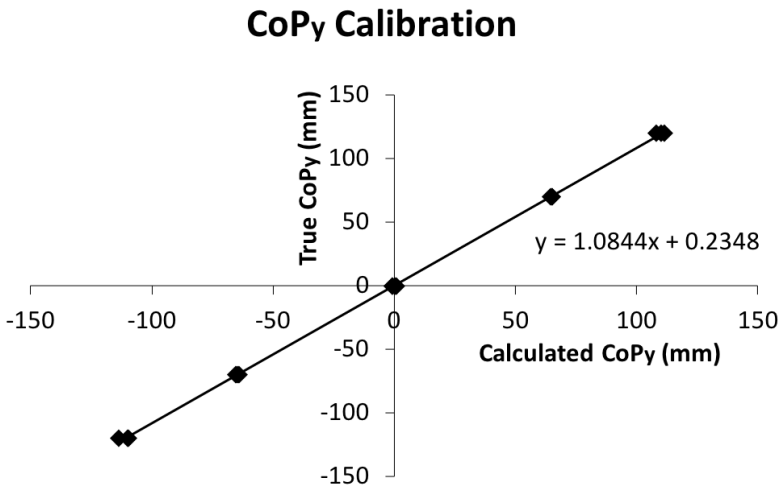

Figure 4: Sample calibration plot for CoP_y.

2.2 Data Collection

Forty-five healthy participants (16 females, 29.3 ± 7.8 yrs, 1.76 ± 0.10 m, 76.0 ± 15.7 kg) were recruited at the 2017 Annual Meeting of the American Society of Biomechanics at the University of Colorado Boulder in August 2017 after providing IRB-approved consent. Data were collected by a number of undergraduate, graduate, and faculty researchers, to demonstrate the approach's ease of use.

All subjects completed an eligibility survey and did not have prior joint replacement surgery, neurologic pathology other than peripheral neuropathy (e.g., Parkinson's disease, dementia), inability to stand or walk without assistance for at least 10 minutes at a time,

persistent pain or pain with moderate ankle movement, or a lower extremity injury that required an assistive device or bed rest within the previous three months.

Severity and history of ankle stability were assessed through a validated self-reported questionnaire, the Identification of Functional Ankle Instability (IdFAI). The IdFAI is a 10-item instrument that covers the severity and persistence of instability during various activities[34] and the instrument has shown superior ability to identify functional ankle instability in individuals compared to other existing questionnaires.[35]

To assess postural control, center of pressure (CoP) data was collected for all subjects during a quiet stance task that consists of standing relaxed on both feet with eyes closed while trying to stay as still as possible on a firm surface (i.e., a balance plate). The eyes closed condition was selected because it has demonstrated superior test-retest reliability[36] compared to other conditions (e.g., eyes open). During the task, a WBB placed on top of a Bertec FP was used to record the subject's CoP (Figure 5). The subject was instructed to stand as still as possible with their eyes closed and the custom LabVIEW program collected data for 60 seconds. This was repeated for three trials.

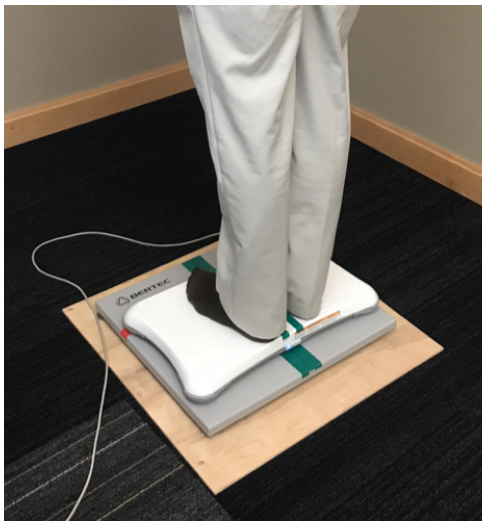

Figure 5: Postural control data collection setup.

Each participant's ankle JPS was evaluated using the CoreX Therapy application. Participants' more unstable ankle, from the self-reported IdFAI survey, was tested. If neither ankle was reported to be unstable, the ankle of the dominant leg was tested. An iPod was strapped to participants' foot, as they lay supine on a table unable to see their foot (Figure 6). Each participant performed ten trials of active ankle repositioning. For each trial, the participant started with their sole perpendicular to the ground then actively plantarflexed their foot until they reached the target angle of 15 degrees and were instructed to stop by the researcher. The participant held this position for 5 seconds to learn the angle. The participant then repeated the movement and indicated when they thought they had reached the target angle once again. The researcher recorded the error from target angle of the participant's ankle for each trial.

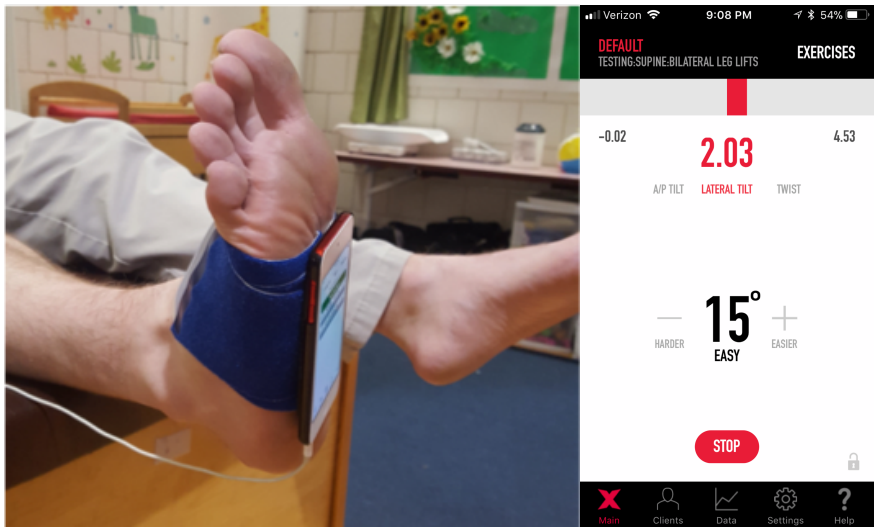

Figure 6: Ankle joint position sense assessment using CoreX Therapy iOS application.

2.3 Reliability of Ankle Proprioception Clinical Tool

Intraclass correlation coefficients (ICCs) were used to assess the trial-to-trial reliability of participants' absolute error in active joint reposition sense. To determine how the reliability changed with the available number of trials, an iterative analysis was performed. ICCs were

calculated considering the first five through all ten trials. The reliability of each number of trials was assessed with and without the most and least accurate trials included.

2.4 Ankle Proprioception and Postural Control Assessment

Postural control was quantified using the data collected from the Bertec FP. The medial-lateral root mean squared (RMS) excursion, mean medial-lateral velocity of the CoP, and the CoP ellipse area were calculated for each balance trial then averaged for each subject's three trials. The average absolute error with the most and least accurate trial excluded in ankle repositioning was used as the measure of ankle JPS. A linear regression of the ankle proprioception measure was analyzed as a predictor of the postural control parameters to establish the relationship between ankle joint position sense and postural control.

2.5 Ankle Proprioception and Ankle Instability Assessment

Participants were classified as having ankle instability if they scored eleven or greater on the IdFAI. This cutoff score has been established as a reliable threshold for identification of functional ankle instability.[34] The average absolute error in ankle repositioning with the most and least accurate trial excluded was used as the measure of ankle JPS.

An independent two-sided t-test (a=0.05) was used to test for a significant difference in active ankle position error between groups with and without ankle instability. Additionally, the Pearson correlation between ankle position error and IdFAI score was used to investigate a continuous relationship between ankle instability and JPS.

Chapter 3: Results

3.1 Reliability of CoreX Therapy Application

The ICCs for five through ten trials are shown below in Figure 4. The reliability of using the CoreX Therapy app as a measure of ankle active JPS generally increased with increasing number of trials included. The reliability was always greater with the most and least accurate trial excluded. When analyzing only the first five and six trials and not excluding the most and least accurate trials, the test had poor reliability (ICC(1, k) < 0.50). All other scenarios resulted in moderate reliability. The most reliable measure of JPS was achieved by collecting ten trials then excluding the most and least accurate trial with an ICC(1, k) of 0.741.

Figure 7: ICCs for active ankle reposition tests.

3.2 Ankle Proprioception and Postural Control Relationship

The linear regression for medial-lateral RMS excursion versus ankle joint position error resulted in a Pearson correlation coefficient of 0.135 (Figure 5). For medial-lateral mean CoP

velocity over ankle joint position error, the Pearson correlation coefficient was 0.176 (Figure 6) and for CoP area versus ankle joint position error the Pearson correlation coefficient was 0.187 (Figure 7). These results indicate that these postural control parameters have a weak to no correlation with ankle JPS.

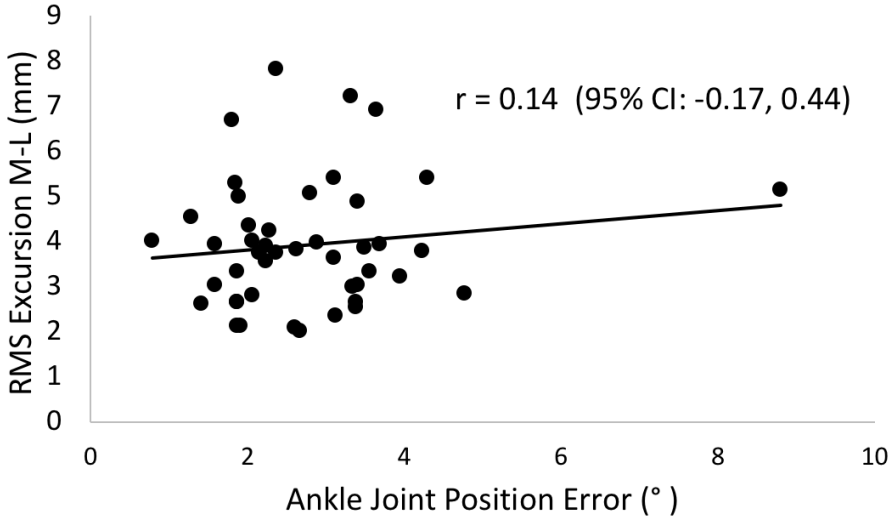

Figure 8: RMS excursion M-L vs ankle joint position error

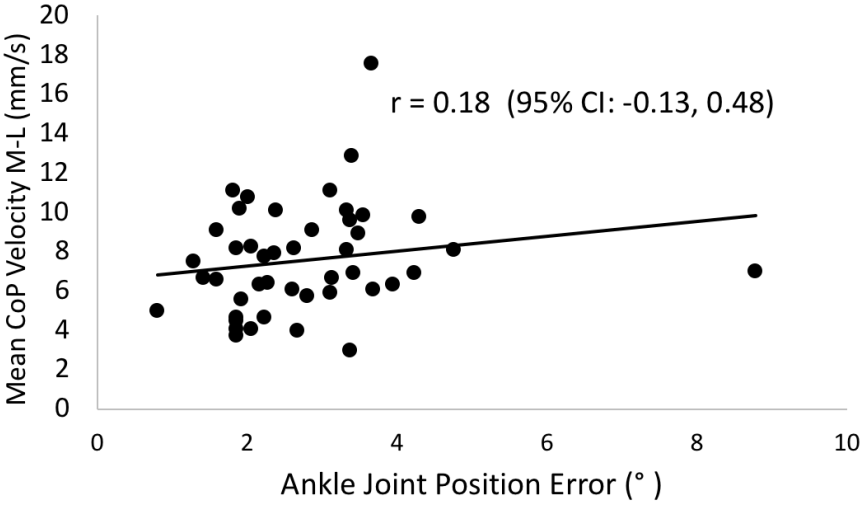

Figure 9: Mean CoP velocity M-L vs ankle joint position error.

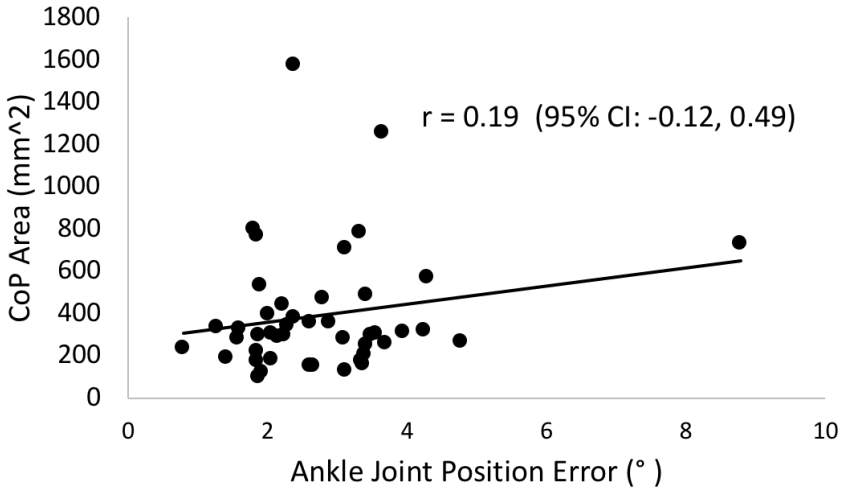

Figure 10: CoP area vs ankle joint position error.

3.3 Ankle Proprioception and Ankle Instability Relationship

The IdFAI classified 20 of the 45 participants as having ankle instability. No significant difference (p=0.21) was observed in the average absolute ankle position error between participants without ankle instability (2.54 ± 0.87°) and participants with ankle instability (3.07 ± 1.63°). Additionally, the low Pearson correlation coefficient (r = -0.08) indicated no relationship between self-reported IdFAI score and ankle joint position error (Figure 8).

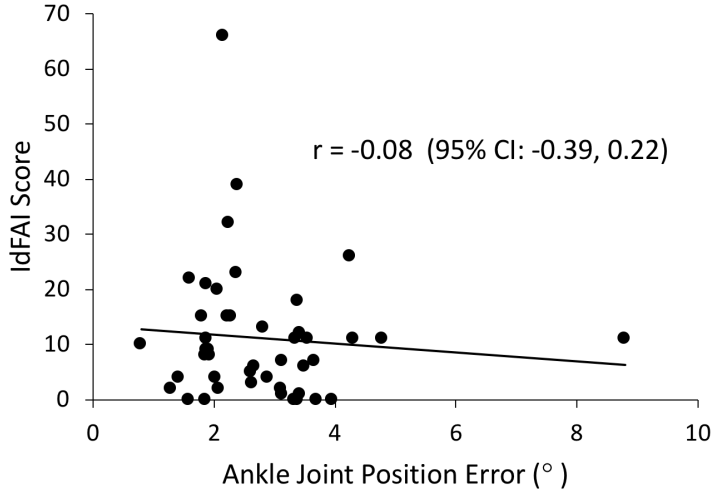

Figure 11: IdFAI score (ankle instability) vs ankle joint position error.

Chapter 4: Discussion

4.1 Wii Balance Board as a Clinical Tool

Most current clinical balance assessments such as the Berg Balance Scale are subjective.[14] These assessments have benefits such as being quick and needing little equipment but have several limitations. Often these subjective assessments have ceiling effects and are unable to detect small changes in patient performance. In addition, when objective CoP measures are compared to these clinical tests, only moderate relationships have been found.[14]

It is essential to objectively assess balance and postural control in the clinic as it can provide detection of small changes in performance over time and better evaluation of the effectiveness of treatments for individuals. It also will allow for increased identification of individuals at risk for falling or musculoskeletal injury so that presentation and rehabilitation measures can be implemented.

The WBB is an ideal tool to implement objective assessment for postural control and balance in the clinic. It is low cost, portable and records CoP measures in the similar way to a laboratory grad FP. Even with limitations such as a low sampling rate and increased noise, it is able to collect data that reliability differentiates between health and impaired populations. It has previously been used to study population with Parkinson's disease,[15] Multiple Sclerosis,[19] and anterior cruciate ligament reconstruction.[16]

4.2 Reliability of the CoreX Therapy Application

The CoreX Therapy application was found to be a moderately reliable tool for evaluating active ankle JPS. For best reliability, ten trials of ankle repositioning should be collected and the most and least accurate trials should be excluded. Collecting more than ten trials of ankle repositioning may increase reliability but is not suggested because fatigue was observed in many

participants as they approached ten trials during data collection. The exact reason why only moderate reliability was seen in using the CoreX Therapy application to assess ankle proprioception is unknown. The ceiling of reliability observed could be a function of the instrument, of the methodological approach for collecting joint position sense, or of joint position sense generally. There is no gold standard to determine which of these factors is the underlying reason for the reliability values in this study.

This tool reduces the barriers to widespread clinical assessment of proprioception as it is low-cost and easy to operate. Materials necessary only include an iPod and a way of securing the iPod to the patient's foot, such as a Velcro strap. Widespread clinical assessment of proprioception can lead to increased implementation of rehabilitative interventions for patients who have impaired proprioception. Additionally, this tool provides improved ability for researchers to directly test relationships between ankle proprioception and other variables of interest rather than inferring proprioception from indirect measures such as nerve conduction velocity or self-reports.

4.3 Ankle Proprioception and Postural Control Relationship

This study found that the postural control parameters of CoP area, RMS excursion in the medial-lateral direction, and mean CoP velocity in the medial-lateral direction have no correlation with active ankle JPS. These results contradict our hypothesis that increasing values for CoP parameters (impaired postural control) would correlate to increased ankle joint position error (decreased ankle JPS and proprioception). This lack of relationship may be because this study examined a healthy population. Generally healthy individuals may have varied ankle proprioception, but perhaps not enough to impact their postural control. Additionally, in healthy populations joint position sense may not be important in postural control because there is very

little motion during a typical quiet standing trial. The tactile sensation of the soles of the feet touching the board may provide more important sensory information than ankle flexion.

Previous research has compared postural control parameters and ankle JPS using the CoreX Therapy application in a population with breast cancer.[28] This work looked at postural control parameters with subjects standing both on a firm FP and on foam. This work saw that ankle JPS was significantly associated with postural control parameters when subjects were standing on the foam. This suggests that there may be a relationship between postural control and ankle JPS between healthy and impaired populations. This relationship may not exist in generally healthy population. Additionally, the task in this study may not have been challenging enough and a more challenging task such as standing on foam may have revealed a relationship between postural control and ankle proprioception.

4.4 Ankle Proprioception and Ankle Instability Relationship

There was no significant difference found in active ankle JPS between subjects with and without ankle instability and a low Pearson correlation coefficient ($r = -0.08$) further indicated that there is no continuous relationship between these two measures. These results complement previous research investigating ankle instability and proprioception using various methods that also found no significant difference in active JPS. These studies used different methods to quantify both JPS and ankle instability as they used a Biodex and tested the difference between subjects' injured and uninjured ankles.[37,38]

A study by Willems et al. in 2002 investigated ankle JPS in the inversion/eversion plane using a Biodex and determined ankle instability from a clinical diagnosis.[39] Aligning with our results, they did not a significant difference in absolute error for JPS between subjects with and without ankle instability. However, they did finds a significant difference in exact error of active

JPS where they accounted for the tendency of subjects to either overshoot or undershoot the target angle. Further investigation into active and passive JPS and using exact versus relative error is needed to fully elucidate how ankle instability and proprioception are related.

Chapter 5: Conclusions

5.1 Additional Applications and Future Work

The WBB and CoreX Therapy proprioception test are tools that can be implemented in clinically and research settings for many applications. Future work should continue to validate the WBB as an accurate tool for collecting CoP data by comparing the data collected against the Bertec FP data. Comparing calculated output parameters and direct point-to-point comparisons would be valuable to assess the accuracy of this clinically-oriented tool. Further work with the Core X Therapy application should investigate if it is also a reliable tool for assessing passive ankle JPS. Also, the validity of this tool could be established by investigating if this tool can identify difference between healthy populations and populations that are known to have ankle proprioception impairments. In addition, the reliability of the tool could be further established by investing the inter- and intra-rater reliability of using the CoreX Therapy application to assess proprioception.

Further analysis on the data collected in this study could investigate the relationship between self-reported ankle instability from the IdFAI and postural control parameters. Exact error for ankle JPS should also be determined for the subjects in this study and a relationship with ankle instability should be examined. Additionally, investigation into ankle range of motion during a quiet standing task could help elucidate if ankle JPS contributes to postural control and balance

Also further work that continues to the study the JPS and postural control relationship in healthy and impaired populations is needed to increase understanding of the correlation between the two.

5.2 Summary

This research developed a WBB into a tool able to collect CoP data for assessing postural control in the clinic. The custom LabVIEW program is able to connect to the WBB wirelessly using a Bluetooth connection and provides an affordable and portable alternative to using a laboratory grade FP. This will encourage widespread clinical assessment of postural control parameters that are known to be impaired in certain clinical populations. Increased clinical assessment of postural control can lead to increased identification of at-risk individuals for falls or other injuries and provided a basis for preventative interventions.

This research also identified the CoreX Therapy app as a moderately reliable tool that can be used to evaluate ankle JPS and proprioception by both clinicians and researchers. The low cost, high portability, and simplicity of this method allows proprioception assessment to be easily implemented in clinical settings. For best reliability, ten trials of active joint position sense should be collected and the most and least accurate trial should be excluded before determining the average absolute error.

Through the use of clinically-relevant tools for measuring both ankle joint position sense and functional ankle instability, this study also identified a lack of a relationship between ankle JPS and self-reported ankle instability. This is the first study investigating this relationship using a clinically-oriented test for proprioception and the IdFAI to characterize ankle instability. This result suggests indicates that functional ankle instability may be caused by factors other than proprioceptive deficits, such as strength deficits or impaired range of motion, and further

research is necessary to investigate whether these or other factors are most important to address in individuals with ankle instability.

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